

Re-Engineering the Mission Operations System (MOS) for the Prime and Extended Mission

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One of the most challenging tasks in a space science mission is designing the Mission Operations System (MOS). Whereas the focus of the project is getting the spacecraft built and tested for launch, the mission operations engineers must build a system to carry out the science objectives. The completed MOS design is then formally assessed in the many reviews. Once a mission has completed the reviews, the Mission Operation System (MOS) design has been validated to the Functional Requirements and is ready for operations. The design was built based on heritage processes, new technology, and lessons learned from past experience. Furthermore, our operational concepts must be properly mapped to the mission design and science objectives. However, during the course of implementing the science objective in the operations phase after launch, the MOS experiences an evolutionary change to adapt for actual performance characteristics. This drives the re-engineering of the MOS, because the MOS includes the flight and ground segments. Using the Spitzer mission as an example we demonstrate how the MOS design evolved for both the prime and extended mission to enhance the overall efficiency for science return. In our re-engineering process, we ensured that no requirements were violated or mission objectives compromised. In most cases, optimized performance across the MOS, including gains in science return as well as savings in the budget profile was achieved. Finally, we suggest a need to better categorize the Operations Phase (Phase E) in the NASA Life-Cycle Phases of Formulation and Implementation.

I. Introduction

The Spitzer Space Telescope is the last of NASA's Great Observatories. Orbiting the Sun in an Earth trailing orbit, the space observatory produced images from extra-solar planets to galaxies at the edge of our universe. Launched in August 2003, Spitzer is cryogenically cooled in a superfluid helium bath allowing the primary mirror to operate from 5.6 K to 12 K in the infrared wavelengths. Spitzer's suite of instruments includes an

Infrared Array Camera (IRAC) to capture infrared light in 3.6 μm , 4.5 μm , 5.8 μm , and 8.0 μm wavelengths, a Multi-band Infrared Photometer (MIPS) with bands in the 24 μm , 70 μm , and 160 μm wavelengths, and an Infrared Spectrometer (IRS) with bands in the 5.2 μm – 14.5 μm , 9.9 μm – 19.6 μm , 14.0 μm – 38.0 μm , and 18.7 μm – 37.2 μm wavelengths. Spitzer's primary mission began after a 90 day In-Orbit Checkout (IOC) and Science Verification (SV) period. When Spitzer's cryogen depleted in May 2009, a series of calibrations known as the IRAC Warm Instrument Characterization (IWIC), determined how one of the three science instruments, IRAC, could operate in the relatively warm temperature of 26K. The characterization period determined IRAC could continue to operate at the warmer temperatures in two of the four wavelength bands (3.6 μm , 4.5 μm)¹.

The Jet Propulsion Laboratory (JPL) manages the overall mission to include real-time command, monitoring, and data accountability. The Spitzer Science Center (SSC) at Caltech provides science planning and instrument operations, while engineering operations and support is provided by Lockheed Martin Space Systems in Littleton,

Phase	Start and End Dates
Launch	2003-08-25
In-Orbit Checkout and Science Verification (IOC/SV)	2003-08-25 / 2003-12-01
Prime (Cryogenic) and Prime Plus Mission *	2003-12-01 / 2009-05-15
IRAC Warm Instrument Characterization (IWIC)	2009-05-16 / 2009-07-27
Extended (Warm) Mission *	2009-07-27 / 2012-12-31

Table 1. Spitzer Mission Phases (* Re-engineered).

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Colorado. A notable achievement is Spitzer's observational efficiency of over 90%, even well into the warm mission. This is double the efficiency of any other great observatories, and Spitzer does it with fewer people².

As seen in Table 1, the Spitzer mission has undergone several mission phases. Whereas each of these phases posed unique challenges to the Mission Operations System (MOS), the scope of this paper will only focus on the prime (cryogenic) mission and the extended (warm) mission.

II. The Spitzer MOS

Before we begin our analysis of the re-engineering processes in the primary and extended mission phase, we must define the Mission Operation System (MOS). The Spitzer MOS contains the people, teams, processes and procedures required to operate the mission. This is distinguished from the Ground Data System (GDS), which is made up of the hardware and software. The GDS includes not only computers and networks, but distributed physical facilities like the mission support areas, the science center and multi-mission facilities. Given that people, teams and processes are necessary to operate the GDS, it is helpful to view the GDS as a subset of the MOS in our discussion of re-engineering.

We discuss the MOS re-engineering using the framework of the uplink and downlink processes (see Figure 1). Uplink processes are the procedures and tools used to develop command products for spacecraft operations and science instrument data return. The observatory operates with pre-planned command sequences developed and uplinked in one-week intervals. These commands can take the form of pre-planned stored command sequences, modules or libraries, or they can be built, radiated and executed in real-time. The prime users of the uplink process are the science users; however, the Observatory Engineering Team (OET) is also a user as they are responsible for the overall health and safety of the observatory.

The downlink process begins with the Deep Space Network (DSN) receiving data downlinked by the observatory. Then, the data are routed to various customers such as navigation, science, spacecraft and instrument engineering, and real-time mission control. The function of the downlink process is not simply the return of data collected on the spacecraft, but also the validation of received data against what was planned in the uplink process.

Although the observatory is a central element in both the uplink and downlink process, according to figure 1, another function, called "packet acknowledgement", is also common to both the uplink and downlink process. The packet acknowledgement process validates the receipt of science and engineering data on the ground collected by the observatory. In order to build commands to retransmit, or delete to free up space on the Mass Memory Card (MMC), each packet of science data must be acknowledged and validated as being received. Therefore, packet acknowledgement is a key function in Spitzer operations. More information on Spitzer's packet acknowledgement process can be found in "Managing the On-Board Data Storage, Acknowledgement and Retransmission System for Spitzer³."

III. The Need for Re-engineering

A. Driving Factors

There are four driving factors for re-engineering. First, changes in mission capability such as Spitzer's loss of cryogen has redefined the science objectives from operating with three infrared sensors to one. Second, as the mission transitions from prime to extended mission, most NASA missions will undergo a reduction in funding profile; re-engineering is necessary for the optimization of the MOS with declining resources. Third, missions with a long life cycle should take advantage of technological advances occurring outside of the space industry. A good example is the rapid rise of smartphone usage in our daily lives. These devices not only improve communications, but also have the computing capability of a desktop computer in the palm of one's hand. Finally, as the MOS progresses into a steady state after launch, lessons learned should be incorporated in order to improve operational efficiency. In fact, re-engineering can be thought of as a method to eliminate unforeseen design inefficiencies that is often revealed as the MOS matures in the operations phase of the mission life cycle.

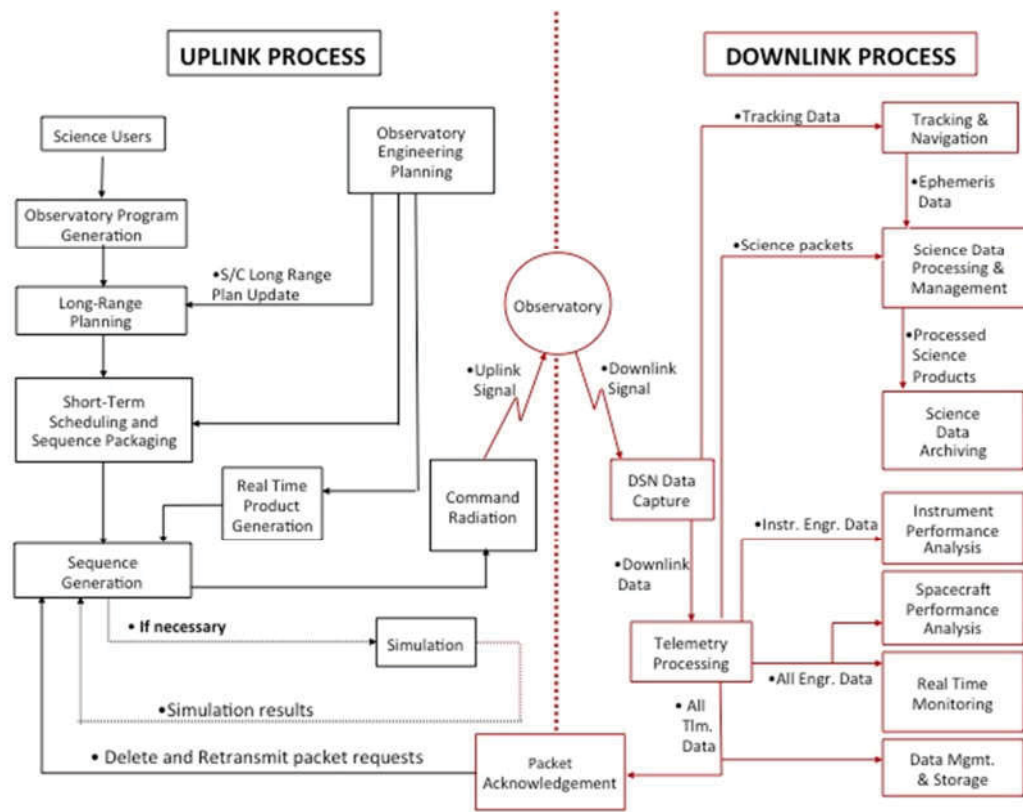


Figure 1. An illustration of the MOS elements using the framework of uplink and downlink process.

B. Spitzer's Re-engineering Path

For the Spitzer Mission, re-engineering is an evolutionary process driven by all four factors discussed previously. During the primary cryogenic mission, we instituted a modest re-engineering effort. The "primary plus" phase of re-engineering evolved based on the steady state of the predefined MOS. Furthermore, an improved understanding of the coupling between the uplink and downlink process, specifically, the telecom link margin, and the MMC data volume allocation, formed the bases for re-engineering in the primary plus phase and continues to this day.

The loss of cryogen and the reduction in the number of science instruments marked the transition from the prime mission to the extended mission. This drove a second MOS re-engineering effort in the extended mission. Also, because of Spitzer's earth trailing orbit, the spacecraft to earth distance gradually increases 0.1 AU per year. This has led to our strategy of maximizing the use of ground antenna resources. Table 2 summarizes each of the MOS elements affected by both the primary plus and the extended mission re-engineering effort.

IV. Re-engineering in Prime Mission and Extended Mission

A. The Uplink Process

A sequence life cycle from initiation to execution on-board the observatory is a 30-day process that includes managing five sequences in various development stages across a five-day period (standard work week). Sequence scheduling for science observations starts the development phase. This phase consists of a calendar driven timeline for tracking activities to include products, reviews, and approvals associated with command sequences. These activities all are designed to support uplink accountability.

MOS Elements	Prime (cryogenic) Mission	Primary Plus	Extended
Sequence Schedule and Review	<ul style="list-style-type: none"> ● Paper Schedule ● Email and Fax 	<ul style="list-style-type: none"> ● Automated Web Calendar ● Discussion Threading with Traceability/Status update ● (Sequence Tracker) 	<ul style="list-style-type: none"> ● Ingesting From Other Databases ● Electronic Approval
Planning Products	<ul style="list-style-type: none"> ● Non-optimized Data Collection 	<ul style="list-style-type: none"> ● Data Volume based on Predicts ● (MMC Prediction Tool) 	<ul style="list-style-type: none"> ● Antenna Elevation Angle
Uplink Summary	<ul style="list-style-type: none"> ● Hardcopies 	<ul style="list-style-type: none"> ● Electronic Forms/Approval 	<ul style="list-style-type: none"> ● Editing Capability
Telecom Link Margin	<ul style="list-style-type: none"> ● Unrestricted (34 m to 70 m antennas) 	<ul style="list-style-type: none"> ● Extrapolated Telecom Link Margin Analysis ● Eliminated Data Dropouts Due to 1-way/2-way mode changes 	<ul style="list-style-type: none"> ● Antenna Scheduled to Optimize Link Margin
Packet Acknowledgement	<ul style="list-style-type: none"> ● Nominal PAP 	<ul style="list-style-type: none"> ● No change 	<ul style="list-style-type: none"> ● Express PAP
Duty Roster	<ul style="list-style-type: none"> ● Laminated Cards 	<ul style="list-style-type: none"> ● Web Based Roster with Electronic Notification 	<ul style="list-style-type: none"> ● Smartphone Interface
Workforce	<ul style="list-style-type: none"> ● Dedicated Teams 	<ul style="list-style-type: none"> ● Limited Cross Training 	<ul style="list-style-type: none"> ● Multi-rolled Staff

Table 1. Re-engineered MOS Elements

1. Sequence Schedule and Review

At the start of the primary mission, the MOS tools used for sequence scheduling and review consisted of paper schedules, and email and fax based communications. As the mission progressed, web based communication tools were introduced to JPL, and the MOS was re-engineered to take advantage of those tools. The tool Spitzer developed in the primary plus re-engineering phase is referred to as the Sequence Tracker (Figure 2).

The Sequence Tracker is a web-based tool that provides a calendar view of deliverables and events associated with the progression from initiation to execution of a sequence activity. The tool serves as a central location for project members with sequence product interfaces to post status as well as track a given sequence related activity. With a click of the mouse button, the web-based calendar expands to show product delivery milestones on a given day. Clicking on the delivery date reveals the familiar folder navigation window pop-up, which allows the loading of a file. Moreover, threaded discussion comment fields below the delivery link allow for open collaborative discussions associated with the delivery. This eliminates disjointed email discussions and the loss of important feedback because someone was left out of the email distribution, while adding traceability for revisions. The addition of the Sequence Tracker in primary plus has added efficiency in the review process, supported better collaboration for remoter partners, and improved searches for archived material. In the extended mission re-engineering, we upgraded the Sequence Tracker with additional automation such as ingesting information from other databases, and electronic approvals of delivered sequence products.

2. Planning Products

In primary plus, an analysis of the overall use of the MMC showed the possibility of filling up the MMC after a missed downlink. The MOS was then re-engineered to include the concept of operating the MMC to operate with a single fault tolerance. A single fault is either the failure to receive the data that the spacecraft transmitted, or the failure to send the commands to free the previous data from MMC storage. To satisfy the single fault tolerant criteria, we calculated data volume based on planned observations and engineering activities and mapped them into the antenna track allocations. This tool is called the MMC Prediction tool.

Declining telecom link margin in the extended mission created a need for planning tools that incorporate telecom performance. One tool, the Antenna Elevation Angle predictor, was developed to help evaluate the supportable data rate based on telecom link margin for a given antenna configuration. This data further aids the science planning process by assuring there is enough telecom margin to support the planned downlink rate. The coupling between the uplink planning process and the downlink telecom margin will continue to be assessed as the observatory's orbit takes it further away from the earth. Finally, the Antenna Elevation Angle predictor combined with accurate data volume predictions give Spitzer the tools to effectively produce highly efficient sequences in the extended mission.

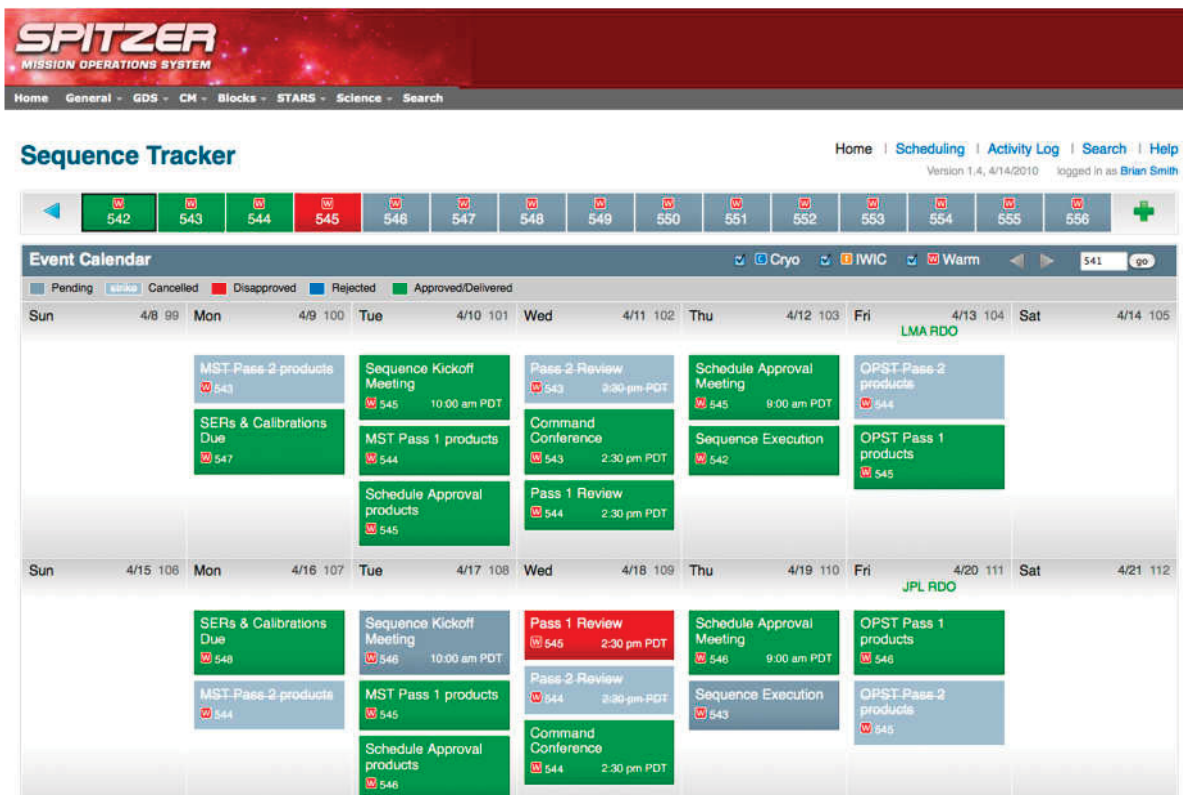


Figure 2. The Spitzer Sequence Tracker

3. Uplink Summary

When command files are approved for uplink, it is summarized in a form known as the uplink summary. This form is used at the command conference to approve the contents and instructions for a given uplink session. Before re-engineering, a hardcopy of the uplink summary was distributed, and when remote teams' signatures were required, it was transmitted via fax. After all required signatures were collected, it was faxed back to JPL for final approval. Those repeated faxes sometimes resulted in hard-to-read products, not to mention introducing delays while transmitting the form. Once web-based tools were further explored in primary plus, the paper uplink summary was re-engineered to become an electronic product. Not only did this eliminate hard-to-read faxes, but it also incorporated electronic signatures, traceability, and electronic archive.

During the extended mission, one of the issues that arose were last minute revisions to the uplink summary that did not impact the validity of the command itself, but rather the directions needed for implementation. As a result, these types of changes did not require another review and signature cycle, and therefore capability for the direct editing of electronic uplink summaries during the command conference was added. Other changes to the uplink summary include the following:

- 1) Automatic revision number appended to uplink summary
- 2) Change the status of previous versions
- 3) A change log is generated for traceability

With the implementation of a web-based uplink summary tool, hundreds if not thousands of paper products that require manual manipulation for retrieval are now replaced by electronic search. This supports rapid response for mission operations.

B. The Downlink Process

At the start of the primary mission, constraints such as the antenna tracking coverage from the DSN and its effect on the telecom link margin were not an issue. Spitzer used 34-meter antennas for tracking, and our maximum downlink data rate was 2.2 Mbps. During the primary plus re-engineering effort, the MOS upgraded procedures, allowing for an extension of the primary mission. This included plans to utilize more diverse tracking coverage

profile such as using a 70-meter, and combinations of 34-meter antennas arrayed to maintain higher data rates over longer durations.

Additionally, the increased spacecraft to earth distance reduced the telecom link margin, which resulted in the need for the MOS to increase efficiency in the use of ground antennas. One way to increase efficiency in a given downlink was to eliminate data outages during the lockup of telemetry signal caused by one-way to two-way frequency transition. This was done by timing the uplink signal such that the ground antenna acquires the spacecraft downlink in two-way mode, therefore eliminating the one-way to two-way transition altogether. Another increase in downlink efficiency came from a decision to skip the “dial tone” sent by the spacecraft during acquisition of signal. The dial tone is present to allow the DSN to achieve lock, but our spacecraft has high enough data rates that the receivers lock instantaneously. Therefore, we now have the option of sending a real-time command to start the playback of science data early, utilizing the dial-tone time for additional science playback.

C. Packet Acknowledgment

We have discussed the coupling of the uplink process to the downlink process driving the need for optimization and re-engineering. However, central to the optimization of data acquisition and return is the Packet Acknowledgement Process (PAP). As illustrated in Figure 1, PAP shares functions in both the uplink and downlink processes. To further explain the uplink/downlink coupling, PAP can be broken up into the following steps.

- 1) Verify the successful downlink of science and engineering data collected by the observatory
- 2) Determine if there are any missed or corrupted data packets
- 3) Build commands to retransmit any missed or corrupted packets
- 4) Free up space on the MMC by generating commands to delete data that has been successfully downlinked

Steps 1 and 2 are part of the downlink process and data accountability, while steps 3 and 4 are part of the uplink and planning process. The routine execution of PAP after each downlink leads to the successful management of the MMC, which is crucial to the overall science objectives.

Starting in Primary Plus, improvements to the PAP process to better support single fault tolerance was investigated. The outcome was the development of an additional packet acknowledgment step before the complete data set is received. This new PAP process is called the “Express PAP”. Express PAP is almost identical to the nominal PAP, except it is performed in real-time instead of after the completion of a downlink. Express PAP provides for the real-time validation and deletion of a portion of received data from the MMC.

Additionally, during the prime and beginning of prime plus, the physical ground data network limited Express PAP to a performance level of 3% to 5% of what we planned. Later, during the transition from prime plus to the warm mission phase, an increase in bandwidth based on improvements in the ground network enhanced the performance further to 5% to 15%. Now, several years into the warm mission, the Nominal PAP and Express PAP combination provides a powerful toolset tolerant to single faults, while mitigating possible science loss, and supporting the recovery of lost or degraded performance from DSN antennas.

D. Human Elements

Human factors are always dynamic in any MOS, especially one containing real-time operations. Communications and coordination become key functions in multi-team environments operating in different facilities. Furthermore, workforce and staffing levels can change during the mission life cycle. Improvements to the MOS must address human and team interactions that evolves with the mission life cycle.

1. Duty Roster Notification System

There are multiple types of events during mission operations that require notification of support personnel. Mission operations both in the Flight and Non-Flight environment consist of multiple layers of personnel supporting operations on different work-shifts in both local and remote locations, such as the Caltech campus, Lockheed Martin and Ball Aerospace in Colorado, and universities around the country. To address the following problems:

- 1) Who is the primary and alternate point of contact
- 2) What are their roles and responsibilities
- 3) What is their primary contact (by phone, text message or email)

Spitzer developed the Duty Roster Notification System.

The Duty Roster Notification System provides a centralized service consolidating personnel contact information for notification. The notification system provides rapid notification to a group of roles within the roster using a variety of media devices. A text message with the time, date, and problem description is issued to alert personnel. Through a web-based interface, the user can provide real-time updates for personnel contact and notification information. The display of information is controlled based on user privileges. Figure 3 illustrates how the Duty roster Notification works.

After its implementation in 2004, the Duty Roster Notification System helped Spitzer communicate and coordinate numerous mission critical activities and anomalies. The elimination of laminated contact cards and paper contact lists not only reduce clutter, but also minimize possible confusion and repetitive updates. Moreover, the Duty Roster delegates the update of contact information to the team or individual. In 2012, we updated the Duty Roster to include a mobile interface for smartphones. The success of Spitzer's Duty Roster has created a demand for similar tools for other JPL mission and services. In fact, the same team that developed Spitzer's Duty Roster has now created a version serving multiple missions and services at JPL. Future implementations of the multi-mission duty roster could include external missions with JPL services.

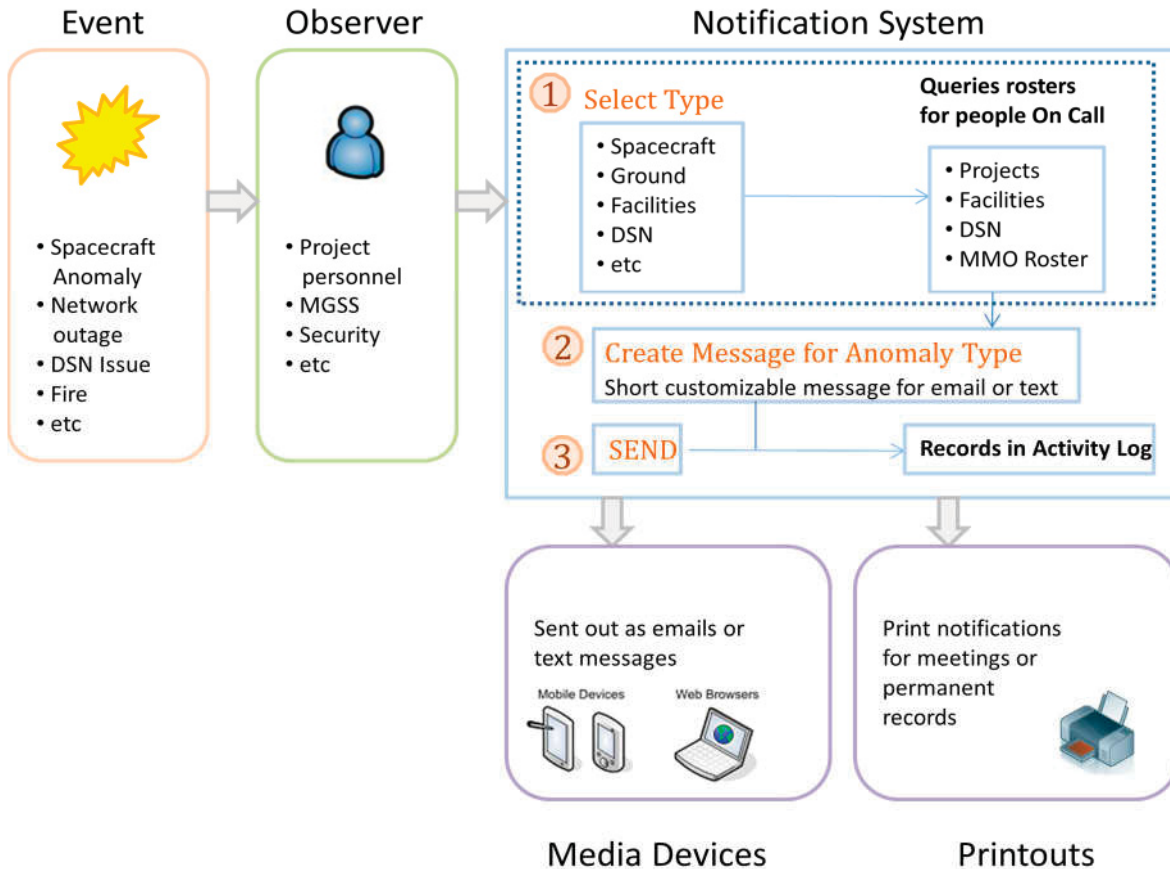


Figure 3. The Spitzer Duty Roster Notification

2. Changes in Workforce Profile

Over the course of mission phases, either by higher resource demand or attrition, staffing profile often evolves. Under these circumstances, one of the biggest challenges for the life cycle of mission operations is retaining a heritage knowledge base. The goal is to preserve heritage experience within the processes of the MOS. Spitzer achieved this by leveraging the knowledge of experienced team lead in the re-engineering improvements that provided new and enhanced tools and procedures. Furthermore, co-location of some teams within the MOS proved to be a catalyst for the exchange of ideas. This was especially critical in the development of the Express PAP process as described in the Packet Acknowledgement, Section IV-C.

V. Summary

A visual representation summarizing the re-engineering processes described in this paper is shown in Figure 4. This figure superimposes Spitzer's mission phases and the re-engineering efforts described in this paper with the workforce profile. As the MOS design matured, confidence in the system allowed us to investigate modest re-engineering steps. Because of the complexity of coupling between the uplink and downlink processes, unintentional

changes could occur if too many changes are made at one time, or if changes are made too quickly. It is important to note that the MOS re-engineering effort is occurring in parallel with nominal operations.

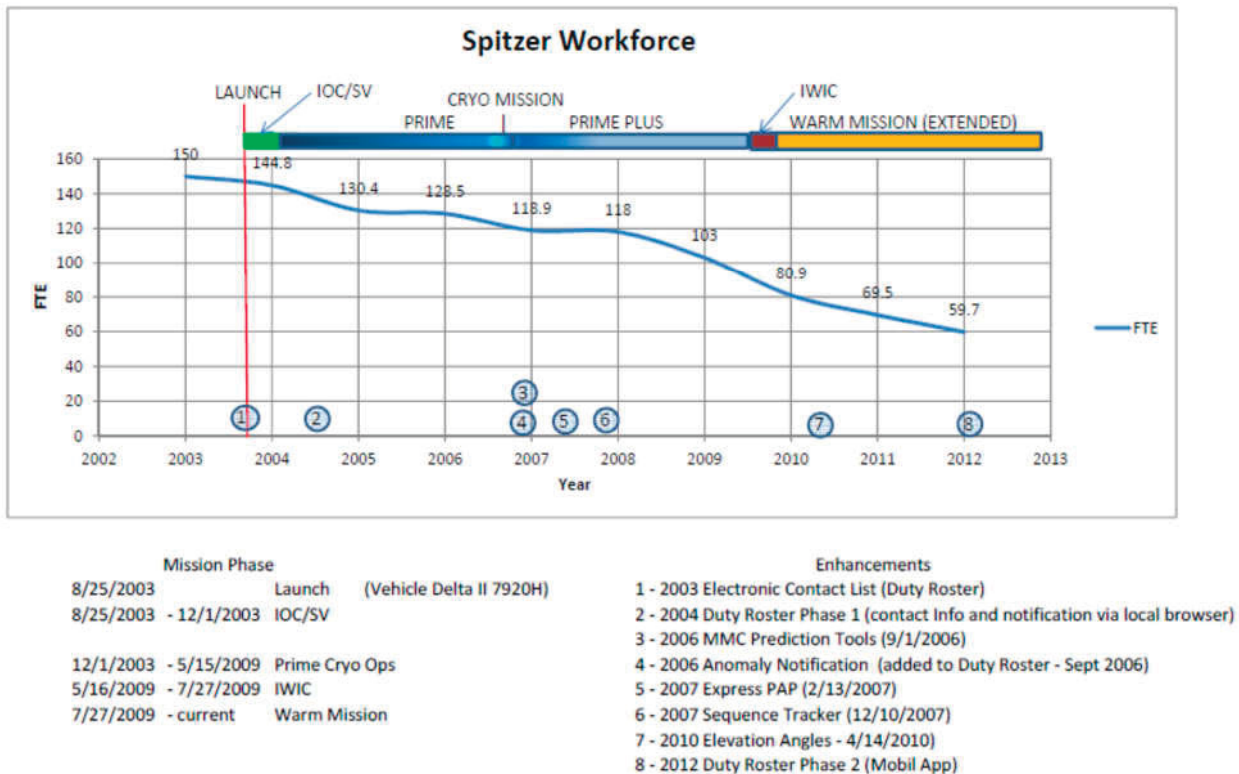


Figure 4 Spitzer Re-engineering Mapped with Workforce

VI. Conclusion

The success of the Spitzer Space Telescope mission is due to the systems engineering standards set forth by NASA, as documented by the NASA Systems Engineering Handbook⁴. Focused mostly on the design and development phases of the mission life cycle, the handbook dedicates only 33% for operations and end-of-life processes. In this paper, re-engineering can be thought of as a method to eliminate unforeseen design inefficiencies that is often revealed as the MOS matures in the operations phase of the mission life cycle. Based on our analysis, we suggest phase E could be expanded with the addition of a formal re-engineering evaluation. Furthermore, even though extended missions are discretionary, the history of recent NASA missions has shown it is a common occurrence. Therefore, we propose the addition of an optional “extended mission” phase between phase E (operations) and phase F (closeout).

Appendix A

Acronym List

AU	Astronomical Unit
DSN	Deep Space Network
GDS	Ground Data System
IOC	In-Orbit Checkout
IRAC	Infrared Array Camera
IRS	Infrared Spectrometer
JPL	Jet Propulsion Laboratory
MGSS	Multi-mission Ground Systems and Services
MIPS	Multi-band Infrared Photometer
MMC	Mass Memory Card
MMO	Mission Management Office
MOS	Mission Operations System
NASA	National Aeronautics and Space Administration
OET	Observatory Engineering Team
PAP	Packet Acknowledgement Process
SSC	Spitzer Science Center
SV	Science Verification

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⁴National Aeronautics and Space Administration, “NASA Systems Engineering Handbook,” NASA SP-2007-6105 Rev 1, 2007.